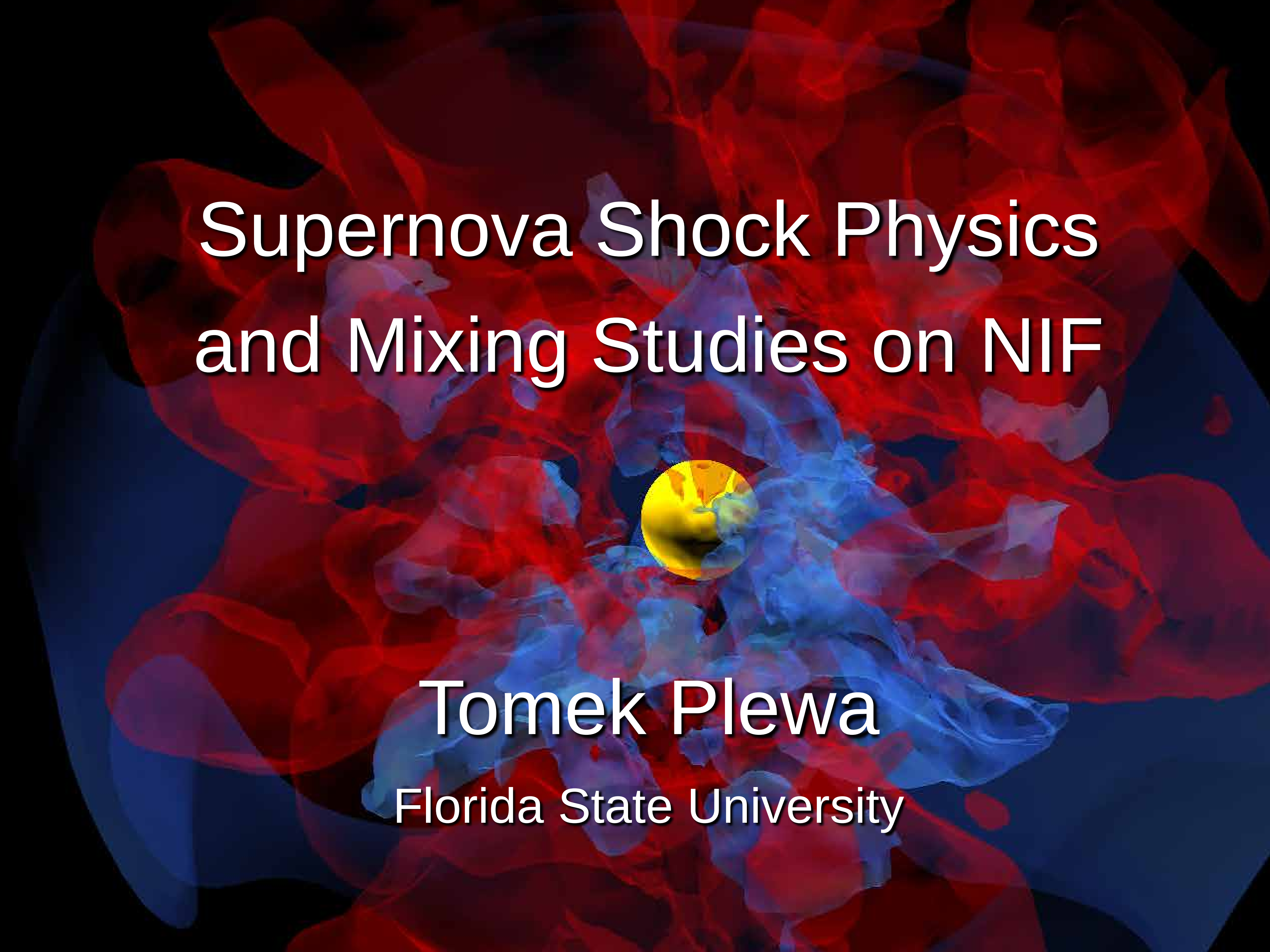


Supernova Shock Physics and Mixing Studies on NIF

Tomek Plewa

Florida State University

Outline

- Purpose
- Method
- Team
- Observations of core-collapse supernovae
- Theory of core-collapse supernovae
- Experiment on NIF
- Discussion

Purpose

- DivSNRT experiment is designed to study and reproduce by means of a well-scaled experimental design the extensive mixing observed in the exploding massive stars.

- DivSNRT experiment will probe fundamental physics of
  - inter-shell penetration outwards to surface via turbulent mixing;
  - shell breakouts;
  - growth of secondary instabilities;
  - vorticity-enhanced mixing.

DivSNRT Team

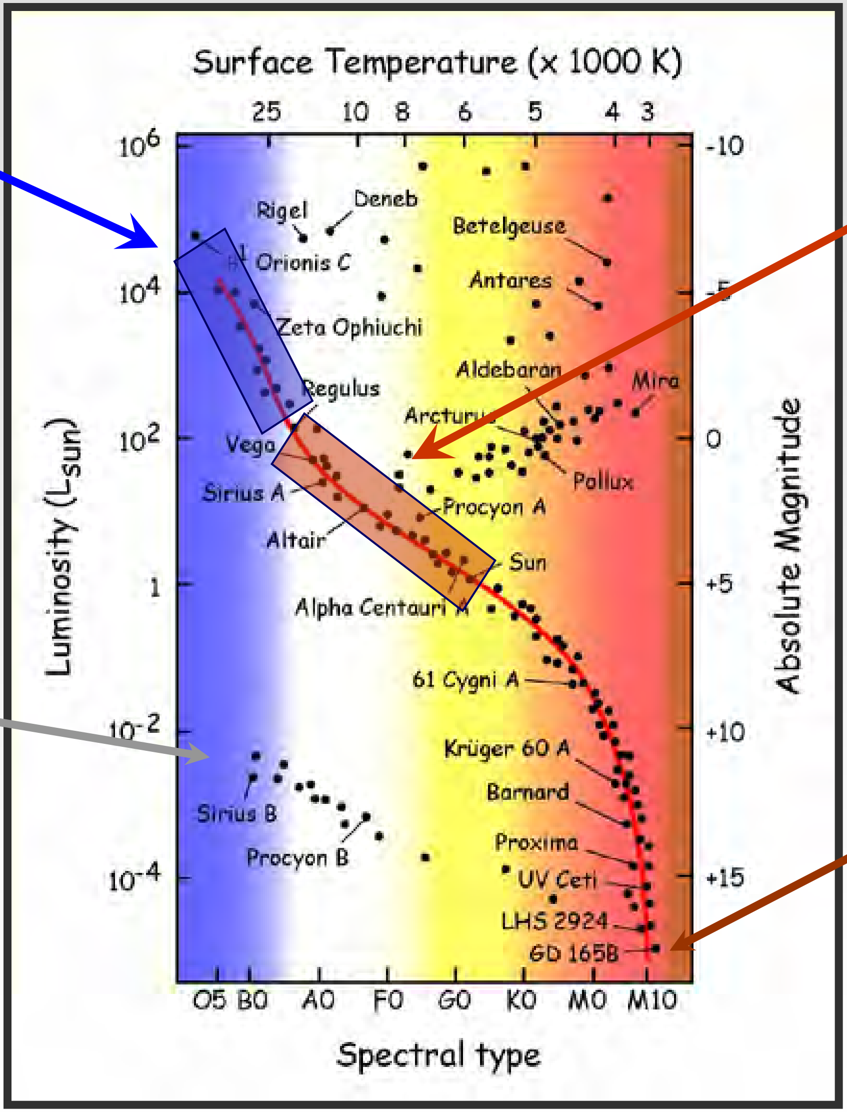
- Paul Drake (experimenter, UM)
- Markus Flaig (designer, UM/FSU)
- Mike Grosskopf (designer, UM)
- Tim Handy (designer, SN hydro explosion, FSU grad)
- Paul Keiter (lead experimenter, UM)
- Konstantinos Kifonidis (designer, SN hydro mixing)
- Carolyn Kuranz (experimenter, UM)
- Aaron Miles (designer, LLNL)
- Frank Modica (designer, multiphysics RT, FSU grad)
- Hye-Sook Park (NIF liaison scientist, experimenter, LLNL)
- Tomasz Plewa (PI, lead designer, FSU)
- Kumar Raman (designer, LLNL)
- Bruce Remington (experimenter, LLNL)

Our Stellar Neighbours

<u>Type II</u>

Massive
Single
H-rich

White Dwarfs
m < 1.4 Msun

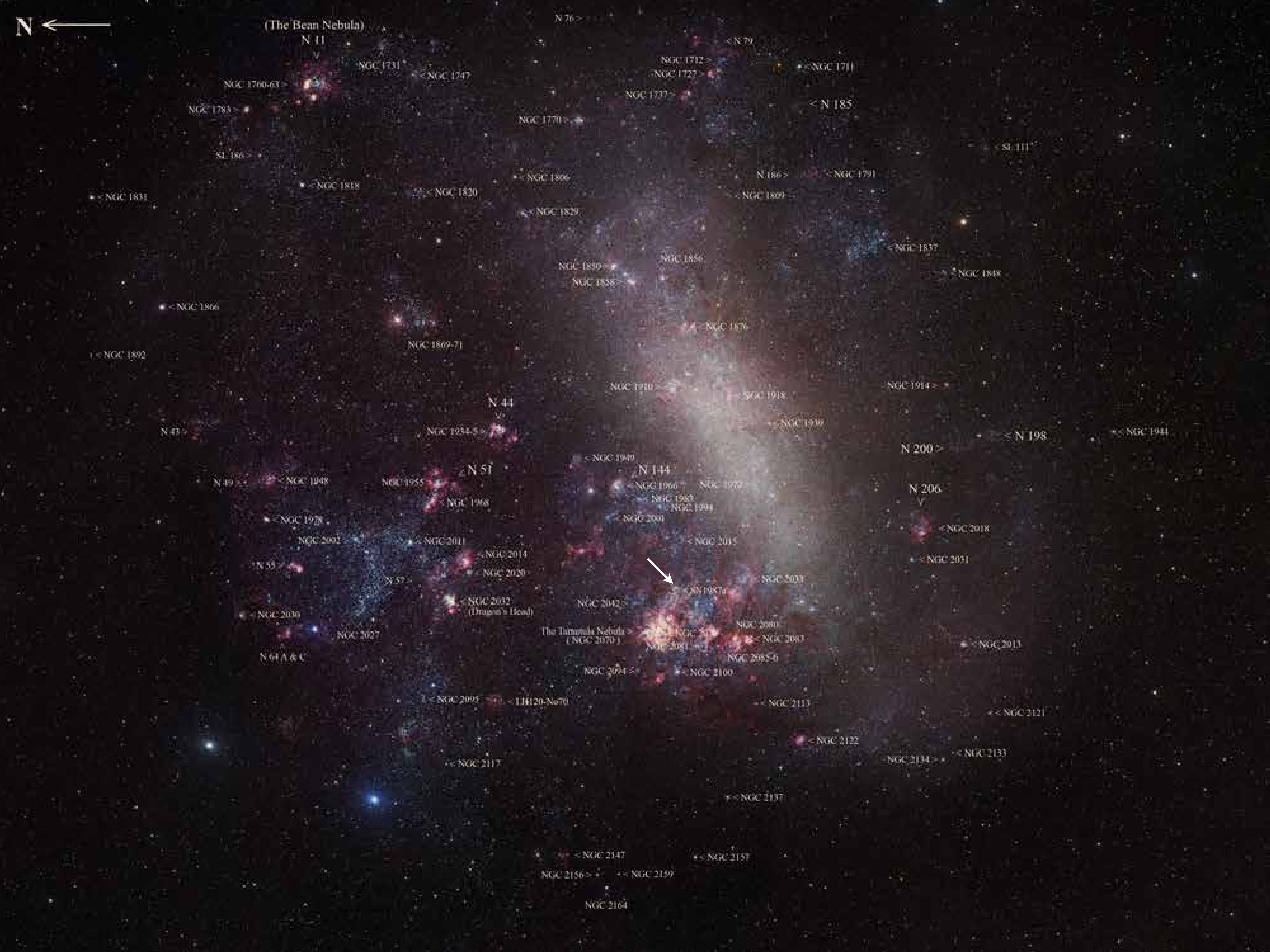


<u>Type Ia</u>

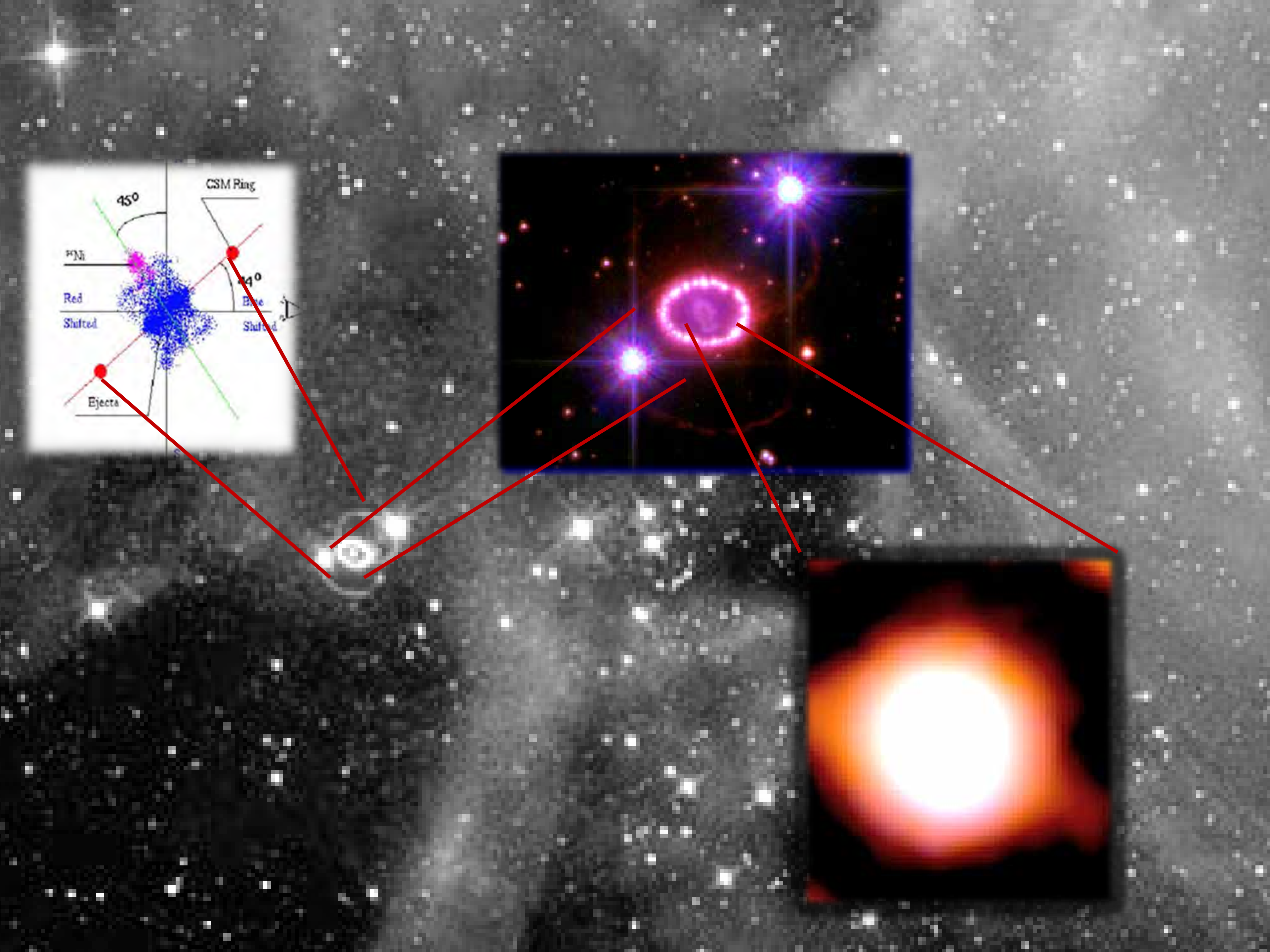
Medium
mass
Binary
H/He-free

Brown Dwarfs
m > 0.075 Msun

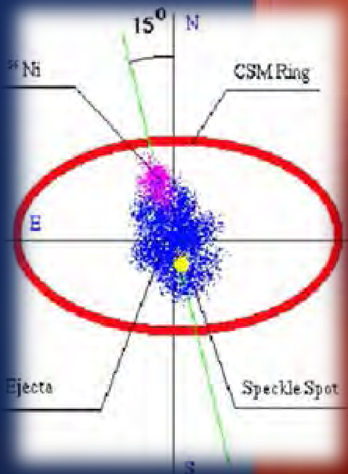

South Celestial Pole
Canopus
Large Magellanic Cloud
Small Magellanic Cloud



N
(The Bean Nebula)
N 11
N 76
N 79
NGC 1712
NGC 1727
NGC 1711
NGC 1731
NGC 1747
NGC 1760-63
NGC 1737
N 185
NGC 1783
NGC 1770
SL 186
SL 111
N 186
NGC 1791
NGC 1806
NGC 1818
NGC 1820
NGC 1809
NGC 1831
NGC 1829
NGC 1837
NGC 1856
NGC 1850
NGC 1848
NGC 1858
NGC 1866
NGC 1876
NGC 1869-71
NGC 1892
NGC 1910
NGC 1914
NGC 1918
N 44
NGC 1939
N 43
NGC 1934-5
N 198
NGC 1944
N 200
NGC 1949
N 144
N 51
N 49
NGC 1948
NGC 1955
NGC 1966
NGC 1972
N 206
NGC 1983
NGC 1968
NGC 1994
NGC 1928
NGC 2001
NGC 2018
NGC 2002
NGC 2011
NGC 2015
NGC 2014
NGC 2031
N 55
NGC 2020
NGC 2033
N 57
SN 1987A
NGC 2032
(Dragon's Head)
NGC 2042
NGC 2030
NGC 2080
The Tarantula Nebula
(NGC 2070)
NGC 2083
NGC 2027
NGC 2013
NGC 2081
N 64 A & C
NGC 2085-6
NGC 2094
NGC 2100
NGC 2095
NGC 2113
NGC 2121
NGC 2122
NGC 2134
NGC 2133
NGC 2117
NGC 2137
NGC 2147
NGC 2157
NGC 2156
NGC 2159
NGC 2164

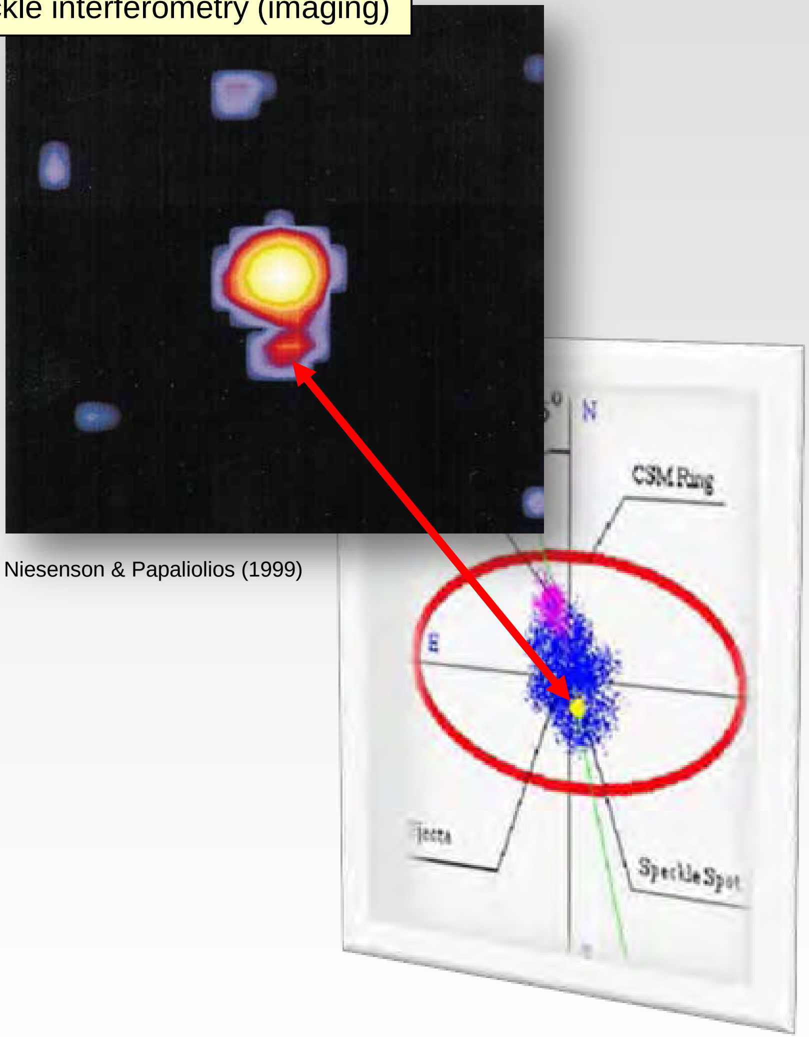

CSM Ring
Red
Shifted
Blue
Shifted
Ejecta


2006


15°
N
56Ni
CSM Ring
E
Ejecta
Speckle Spot
S

Observational Evidence of Mixing

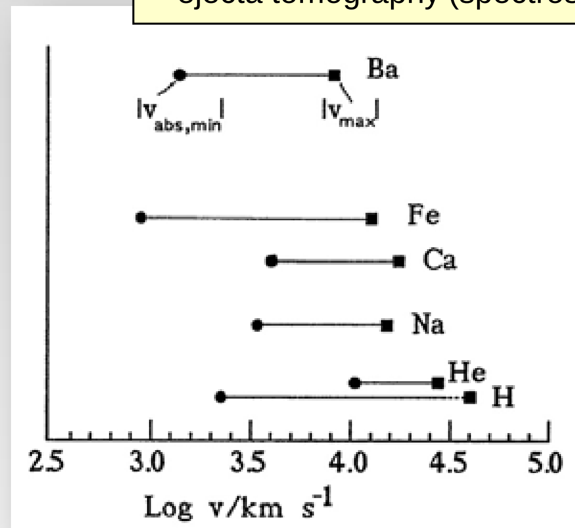
speckle interferometry (imaging)



Niesenson & Papaliolios (1999)

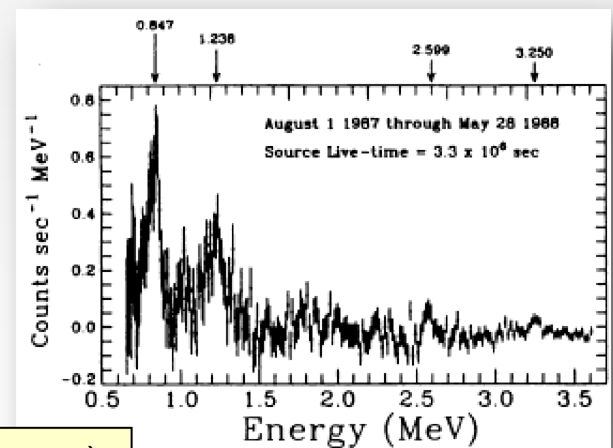
Wang et al. (2002)

ejecta tomography (spectroscopy)



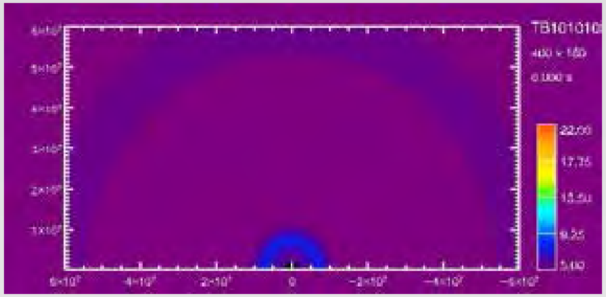
Hanuschik et al. (1991)

gamma rays (spectroscopy)



Leising & Share (1990)

Core-Collapse SN Explosion Theory



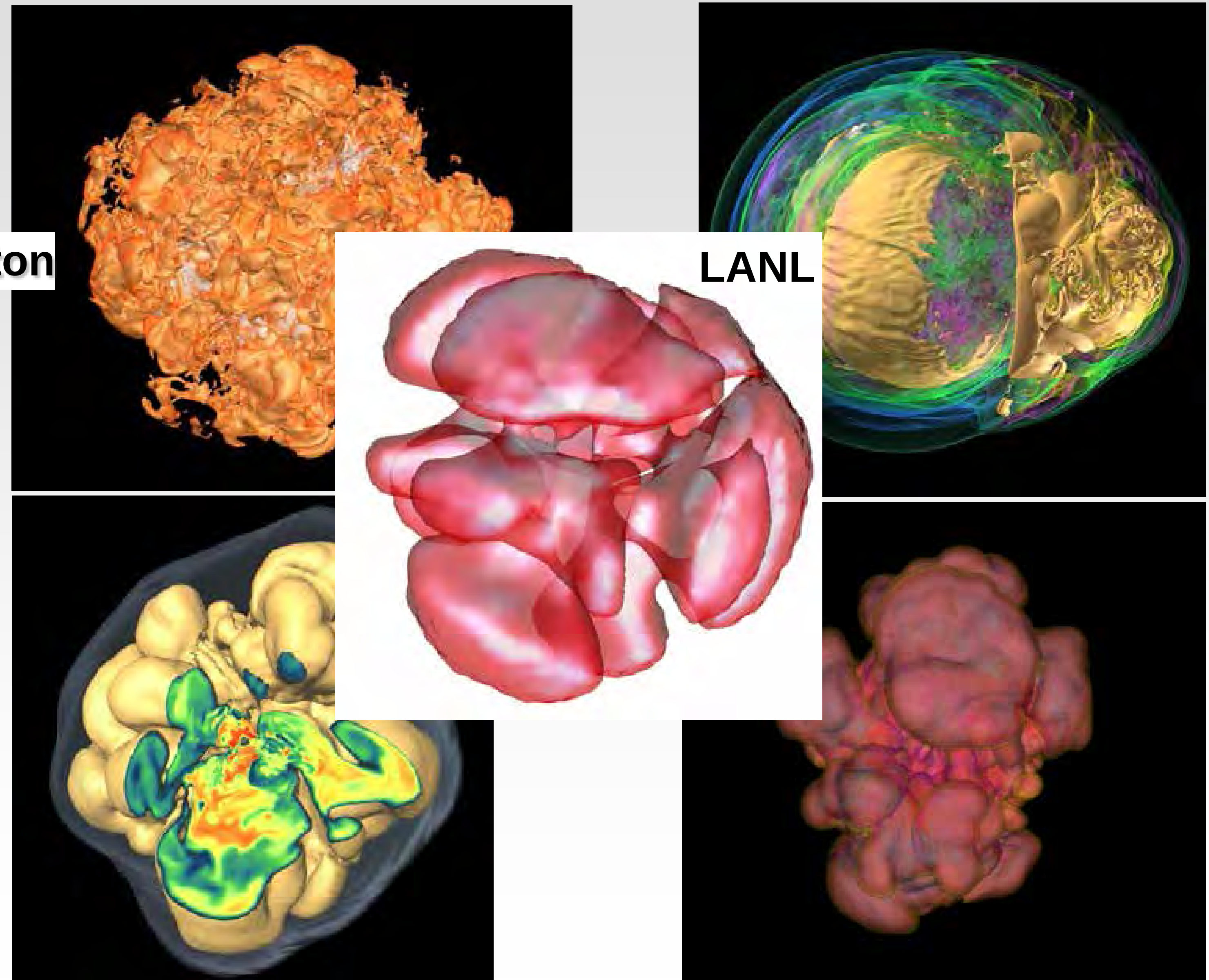
- Massive stars
- Gravity bombs
- Energy extracted by neutrinos
- Accretion shock originally too weak
- Revived by neutrino heating of the post-shock matter

- Once the shock is launched…

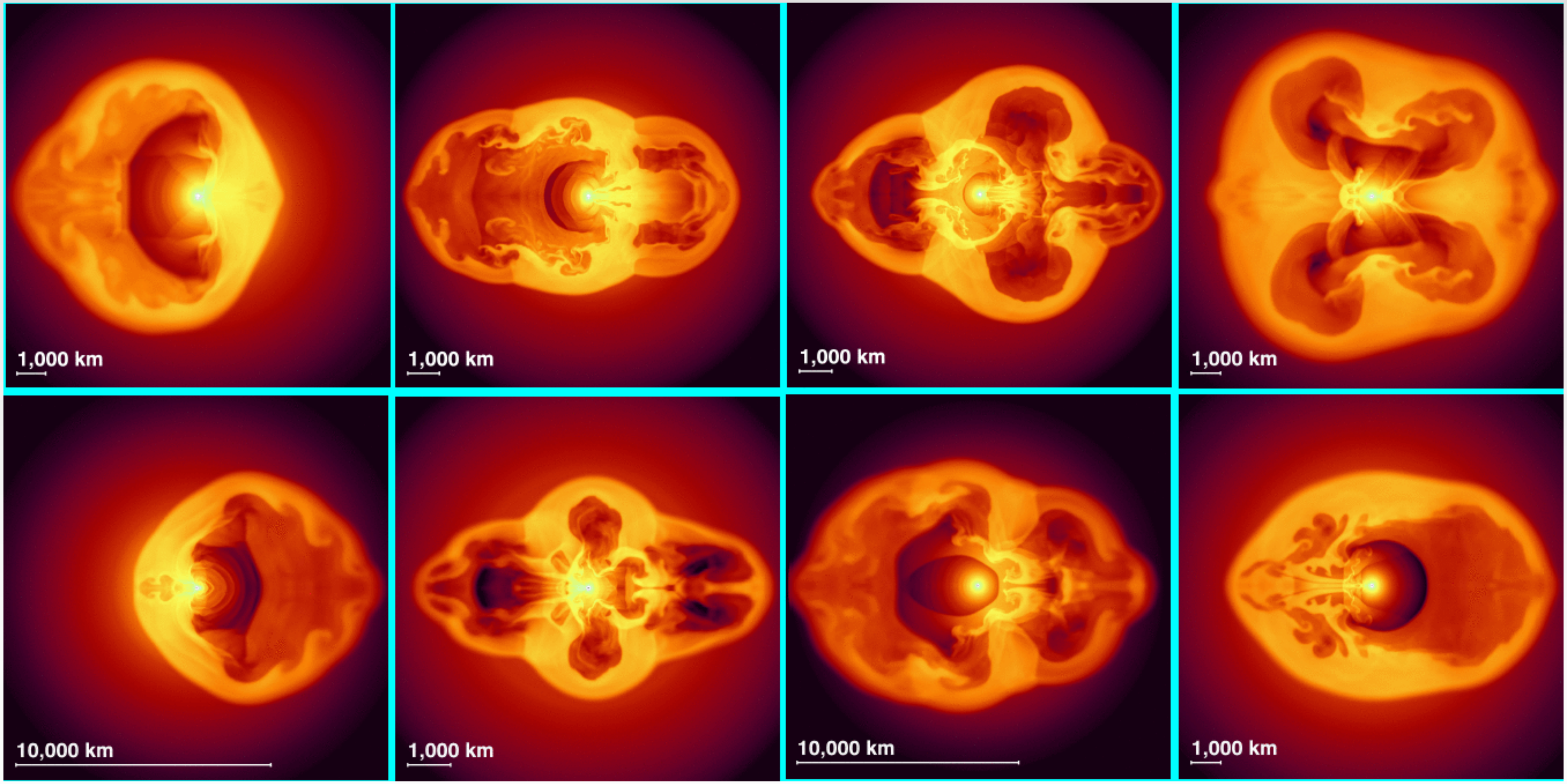
> We used a computational method for explicit hydrodynamics and implicit radiative transfer very similar to that of Christy (1964). The opacity corresponded to a Population I composition. A strong shock wave propagates outward through an envelope of some assumed density structure, transporting energy mechanically outward until encountering regions where photon diffusion dominates the energy transfer. The explosion energy was adjusted to give interesting results.

Falk & Arnett (1973)

ccSN Shock Revival in 3D



Standing Accretion Shock Instability



Janka et al. (2006)

HED Connection to Supernovae

- Motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

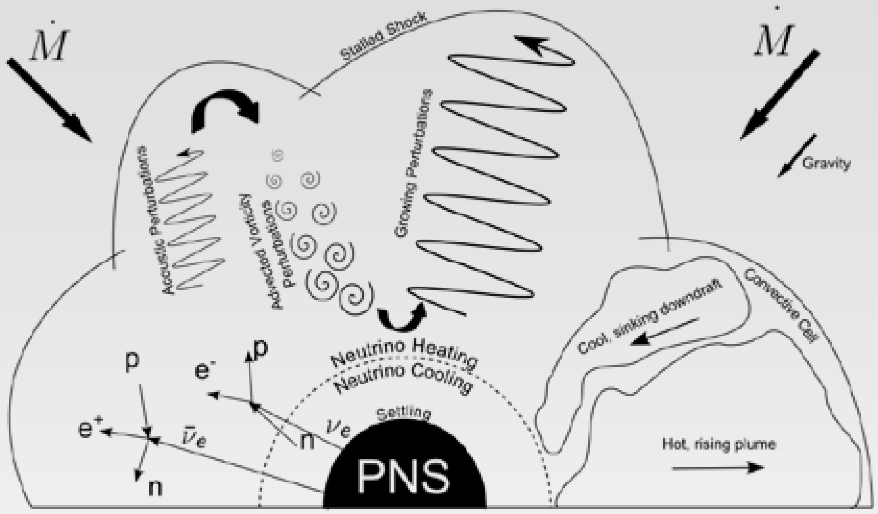
- **Research directions**

  SASI: ccSN explosion poster by Tim Handy

  DivSNRT :ccSN post-explosion RT mixing this talk

NIF SASI Study

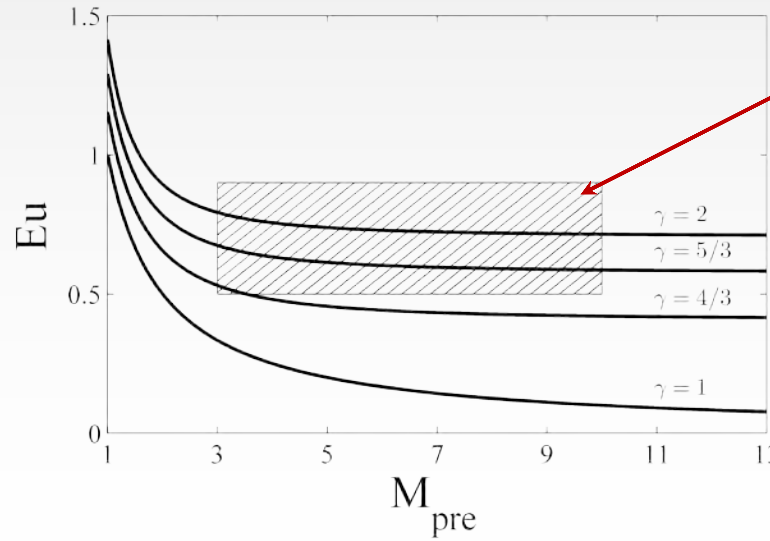
poster by Tim Handy



- HED/SN scaling

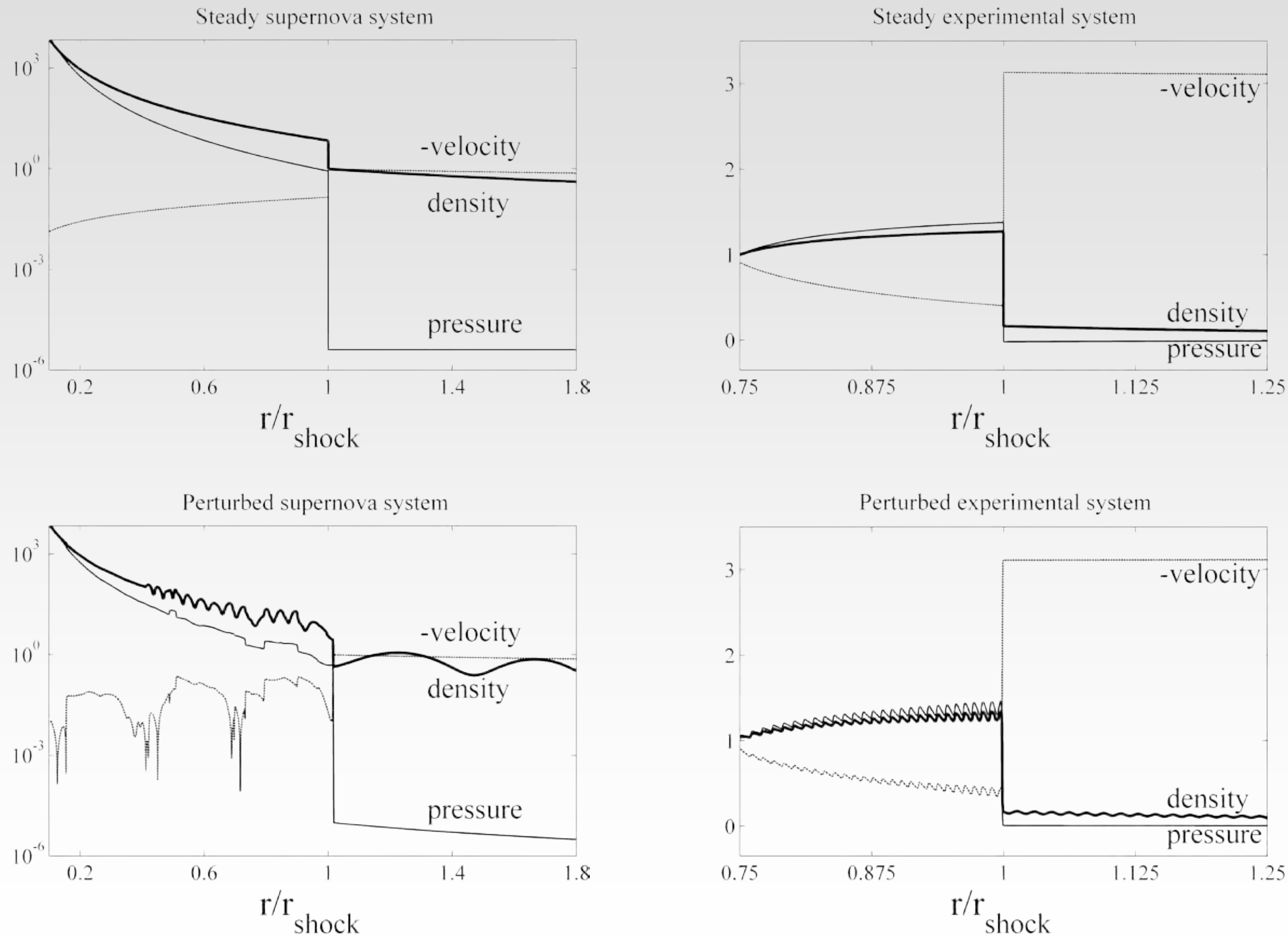
$$(Eu)^2 = \frac{1 + \frac{g-1}{2} M_{pre}^2}{M_{pre}^2 - \frac{g-1}{2}}$$

experimentally feasible region



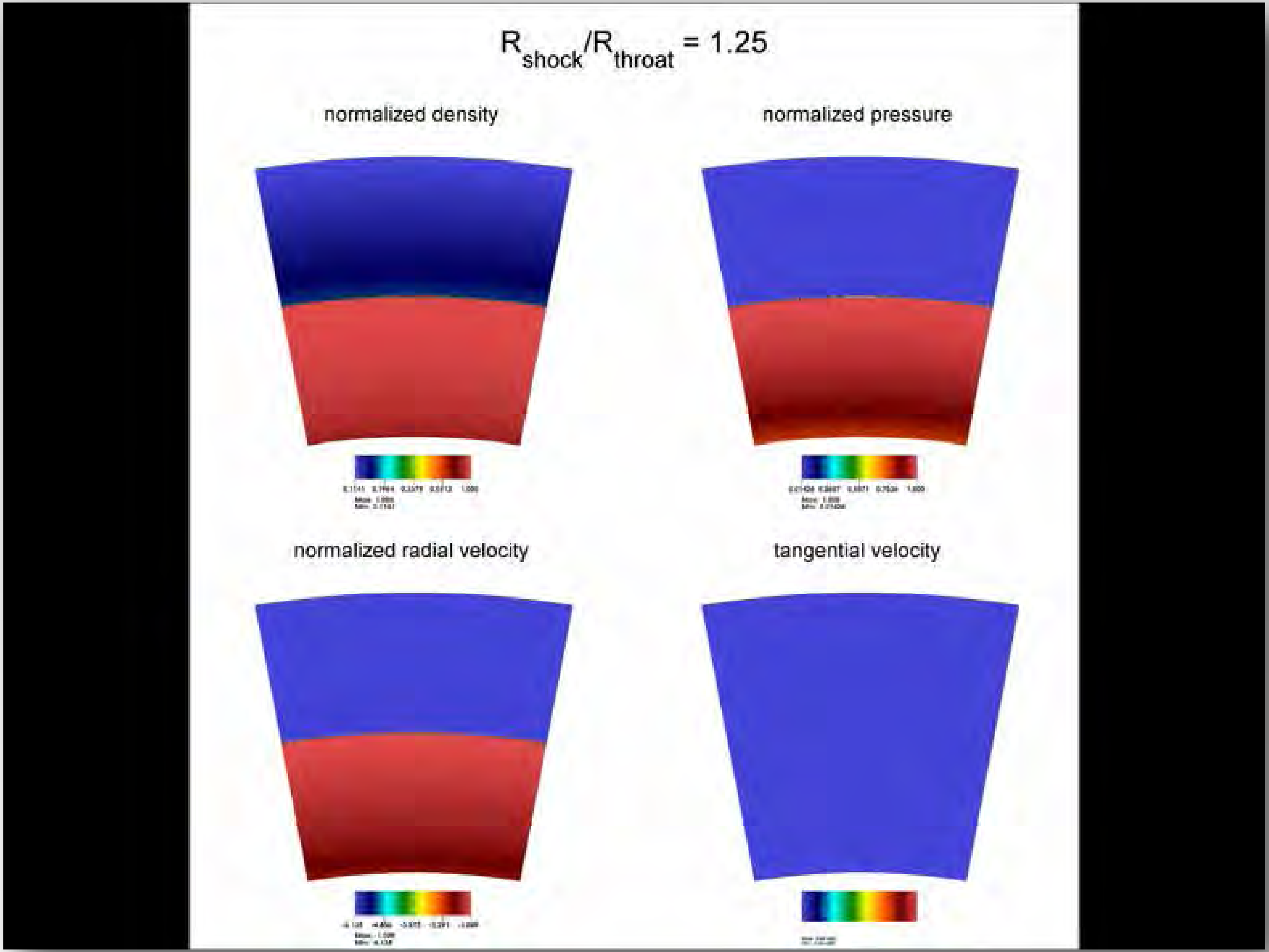
NIF SASI Study

poster by Tim Handy



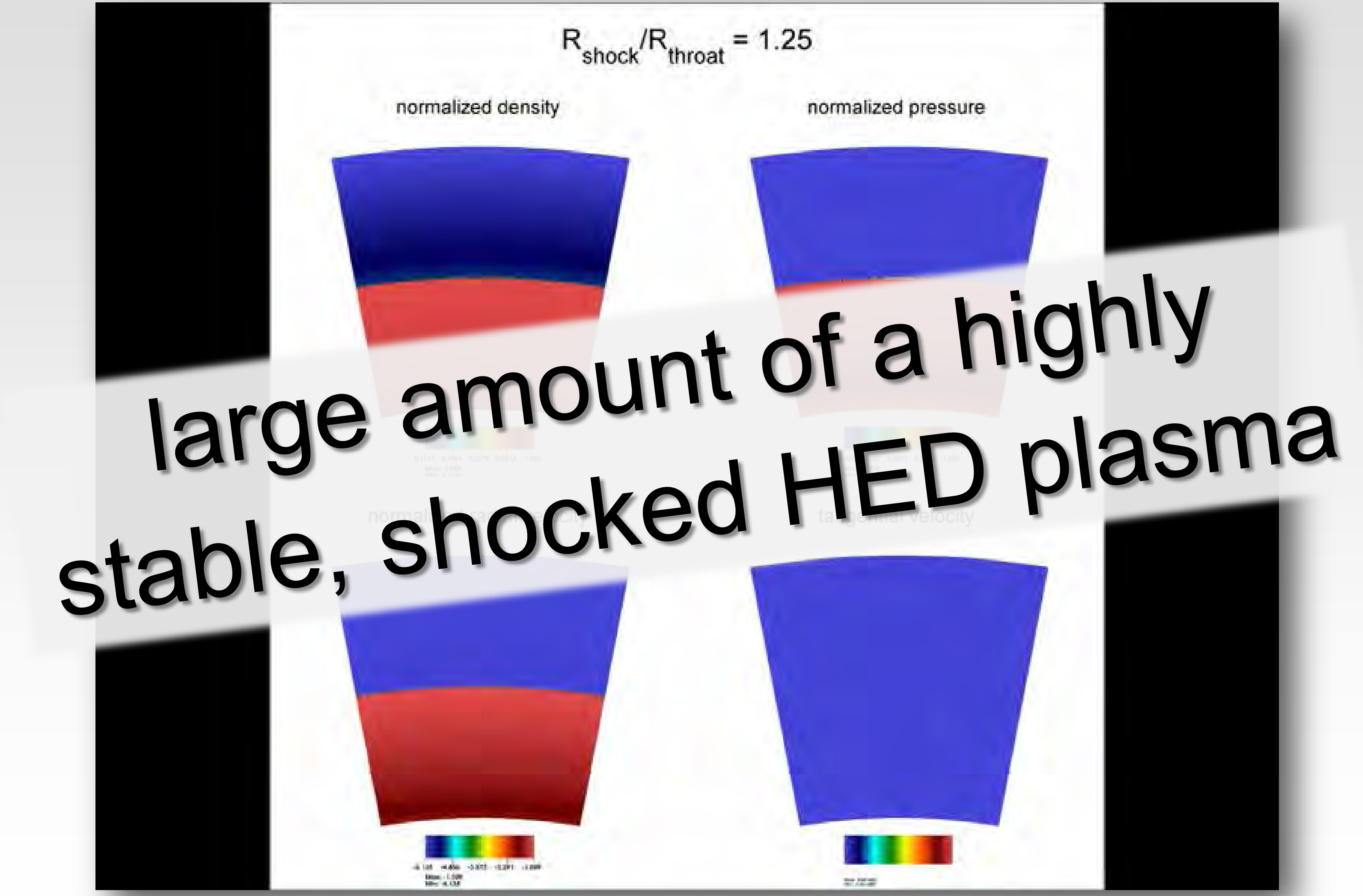
NIF SASI Study

poster by Tim Handy

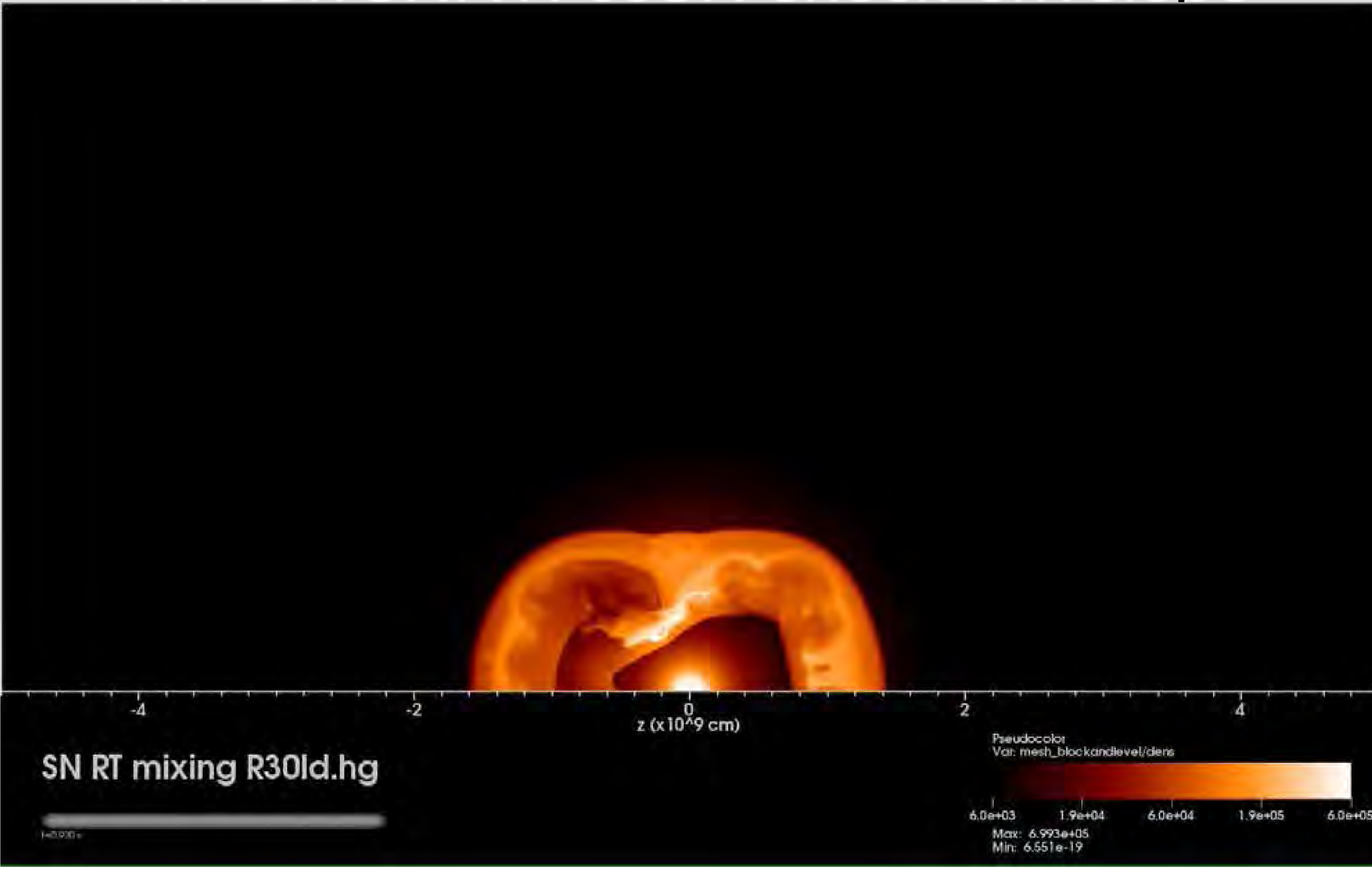


NIF SASI Study

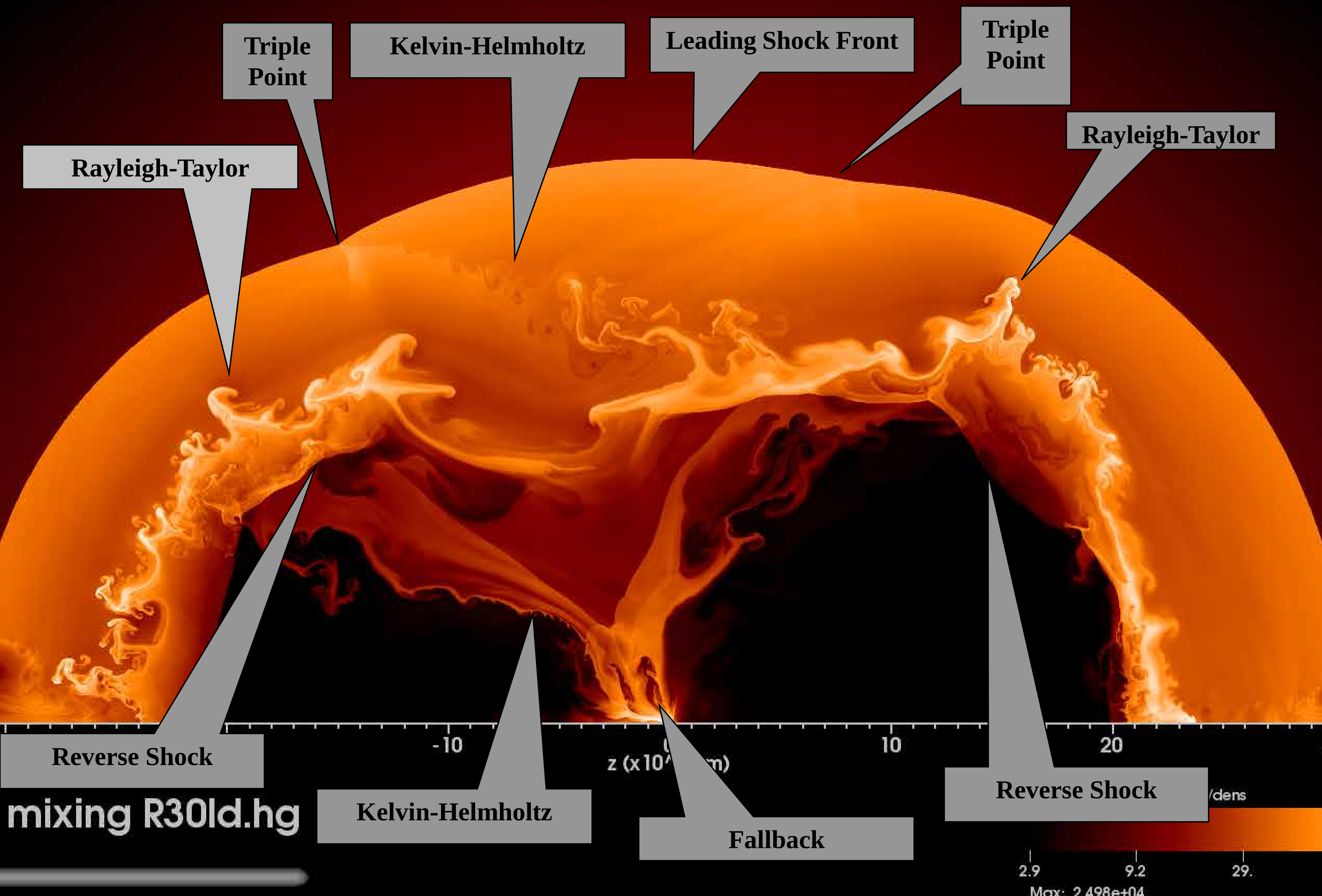
poster by Tim Handy



NIF DivSNRT: ccSN shock-envelope

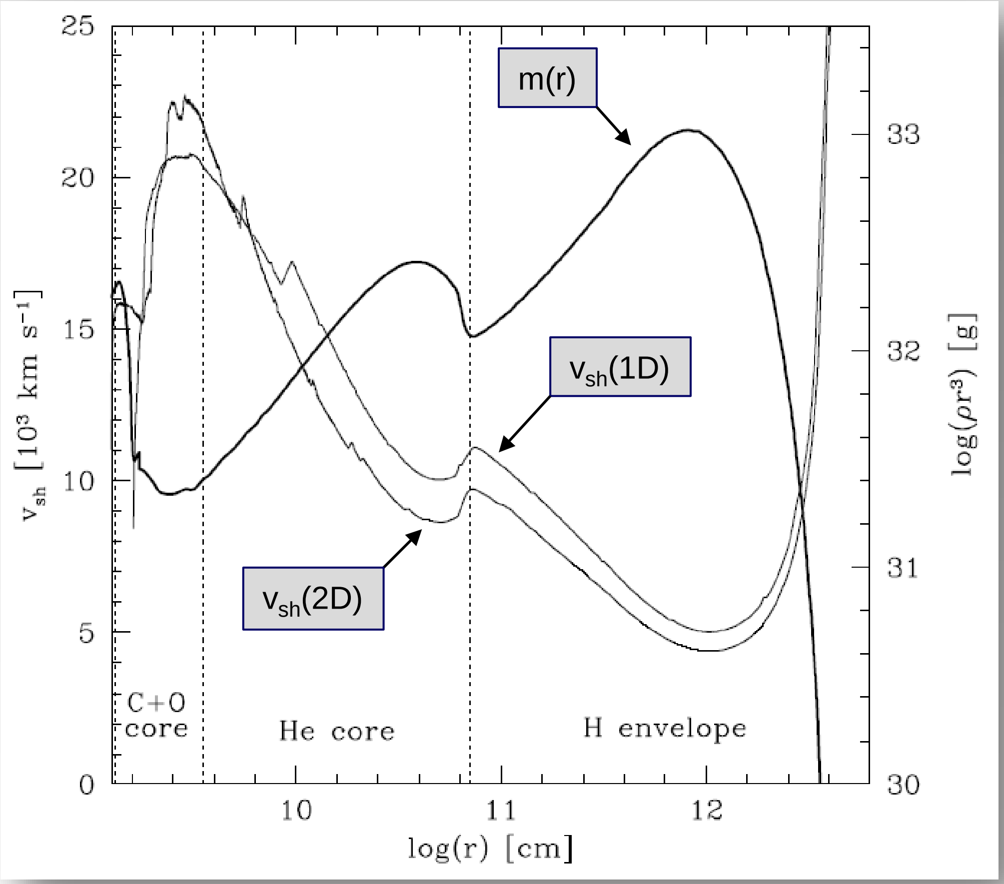


Complex Post-Explosion ccSN Dynamics



Origins of the ccSN RT Mixing

- Time-dependent deceleration of dense layers due to unsteady supernova shock motion though the progenitor envelope



Gawryszczak et al. (2010)

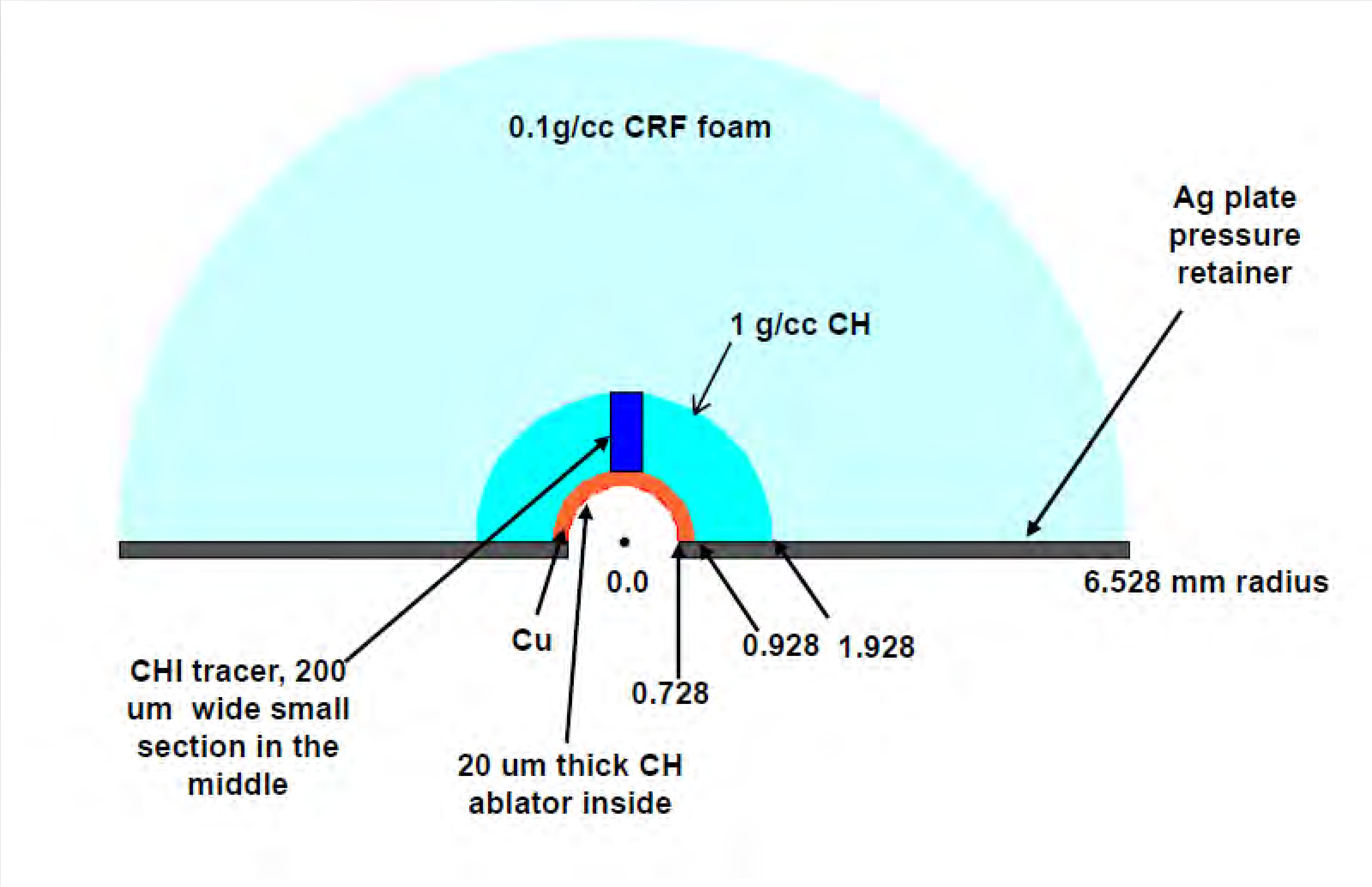
Past HED ccSNRT Mixing Studies

- Motivated by SN 1987A
- Theoretical foundations provided by HED scaling laws (D. Rytuov and collaborators)

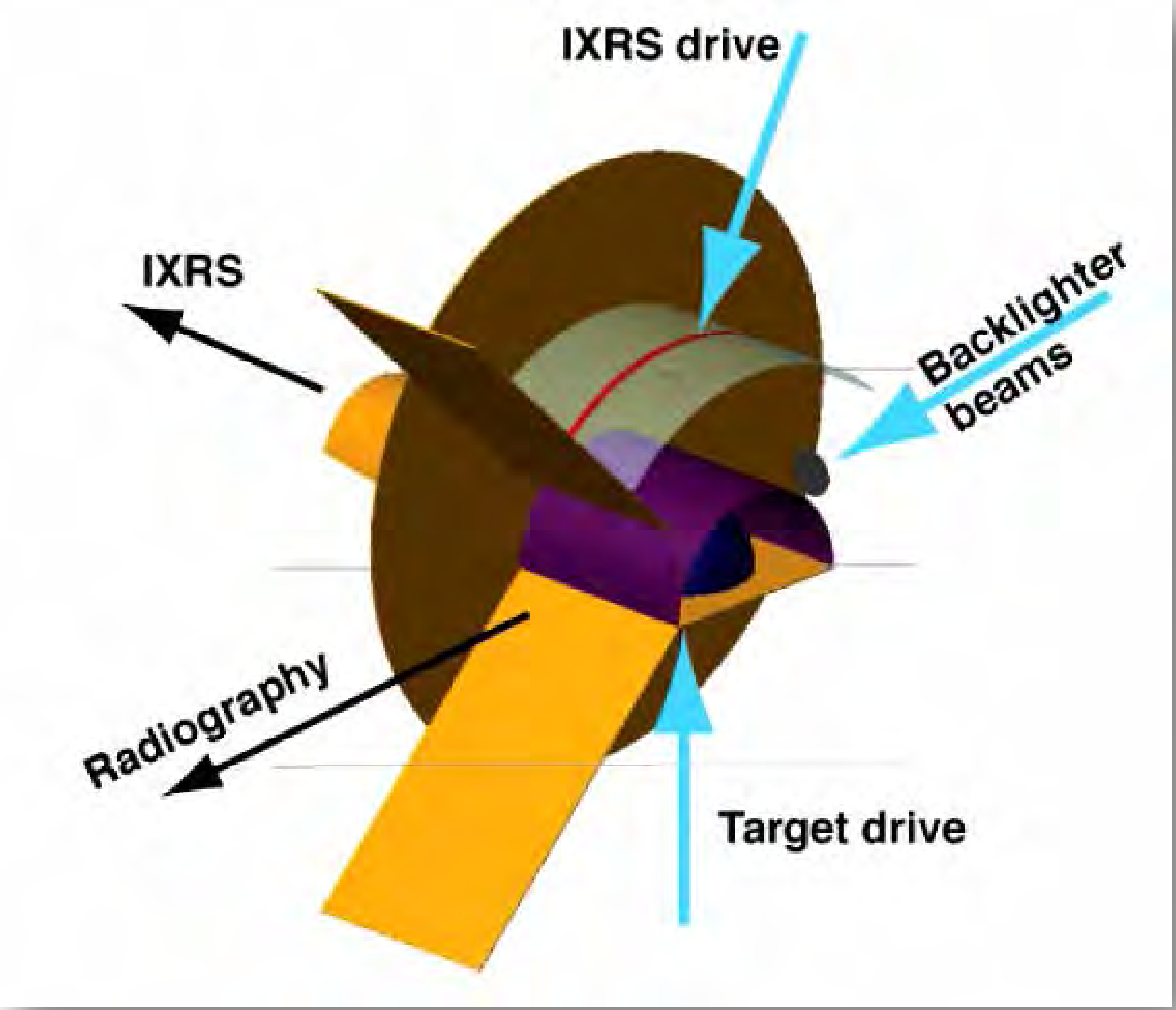
- Most work devoted to planar, two-layer targets (classic RT configuration)
- But SN are largely spherical… => spherical targets and diverging flow configurations, or DivSNRT

- Much more mass involved than in the planar case, thus requiring much more energy to drive
- Early attempts on Omega (Drake et al.) unsuccessful (shell breakup) => NIF!

DivSNRT 3 Layer Target

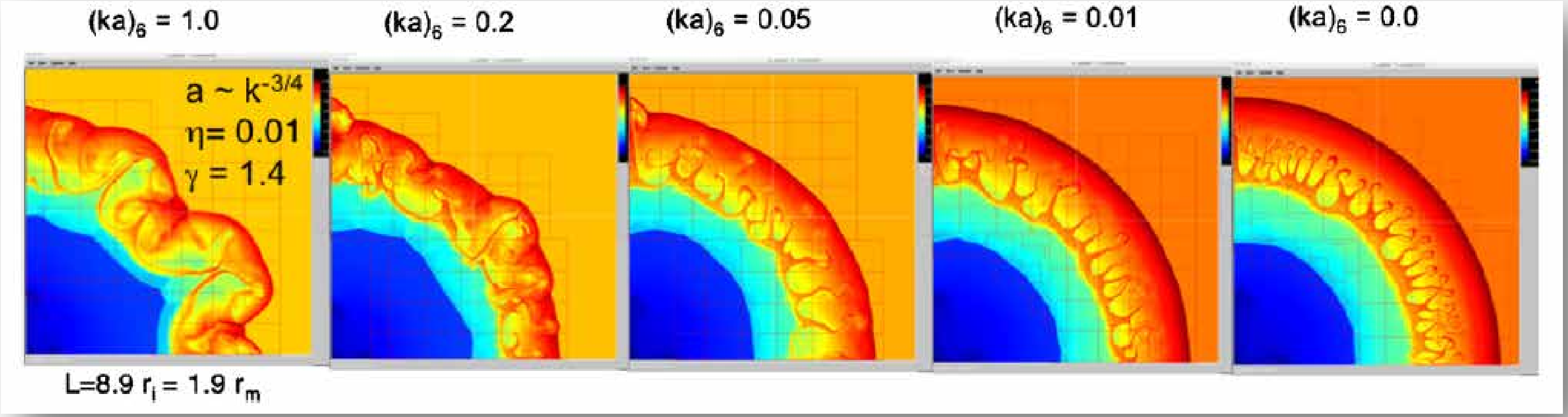


DivSNRT Diagnostics

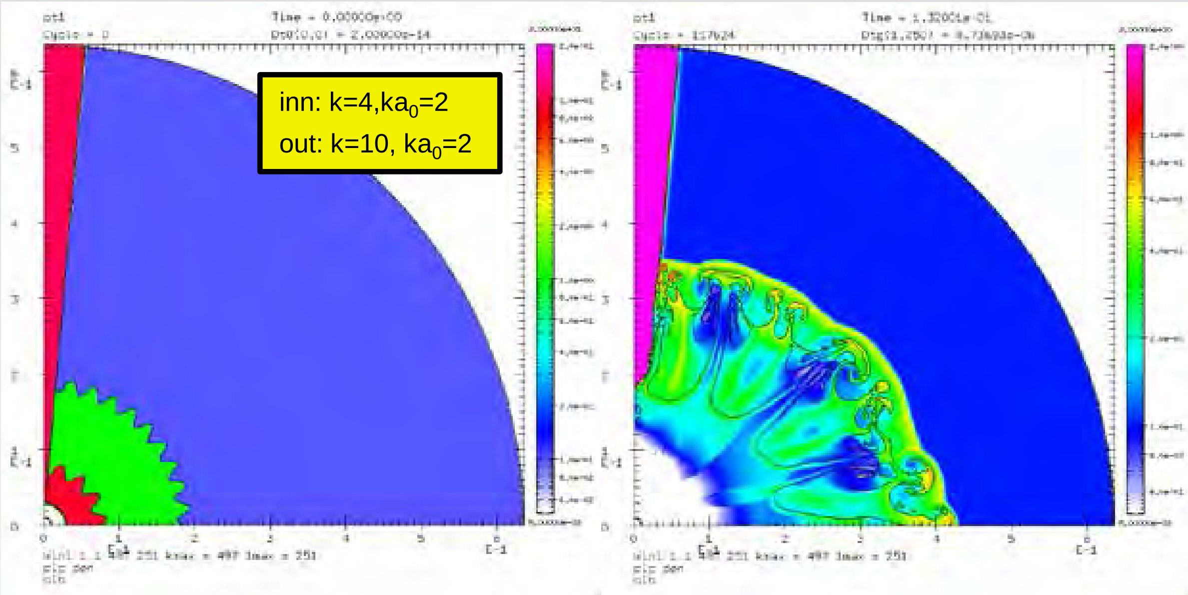


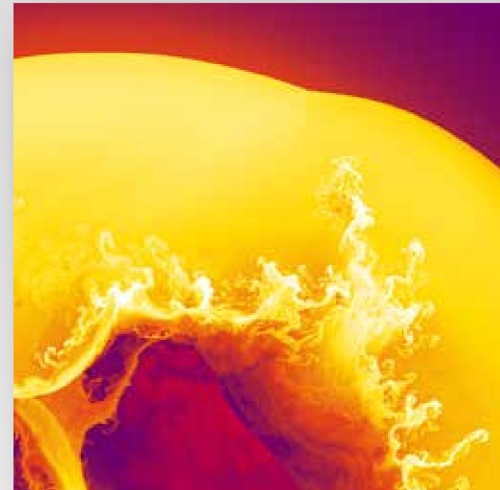
Theory for ccSNRT Target Design

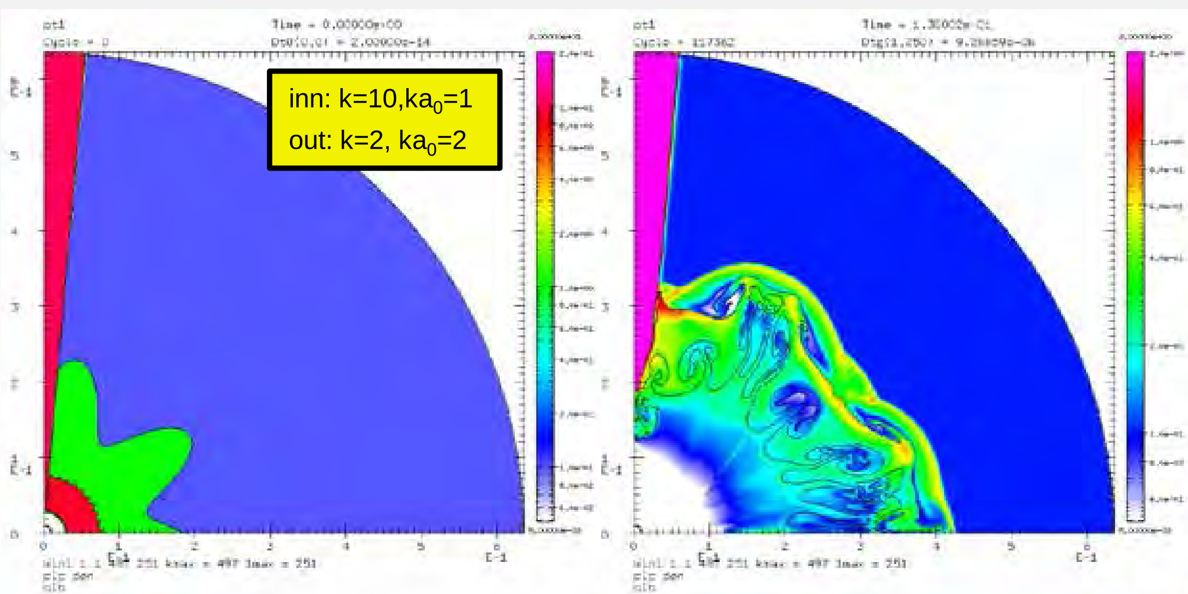
- **Aaron Miles (2009)** analysis of the blast wave instability problem provides analytic framework for target design
- The model combines drag-buoyancy, bubble merger, and assumes (quasi) self-similarity to account for the flow divergence and compressibility effects
- Demonstrates that the memory of the explosion is generally preserved by the system unless modes are very high (higher than considered typical in ccSN)
- High-amplitude perturbations favor RM over RT, at least at early times, resulting in the shock proximity to growing spikes (if $(ka_0) > 1/3$ for adiabatic index 5/3; if $(ka_0) > 0.2$ for index 4/3).

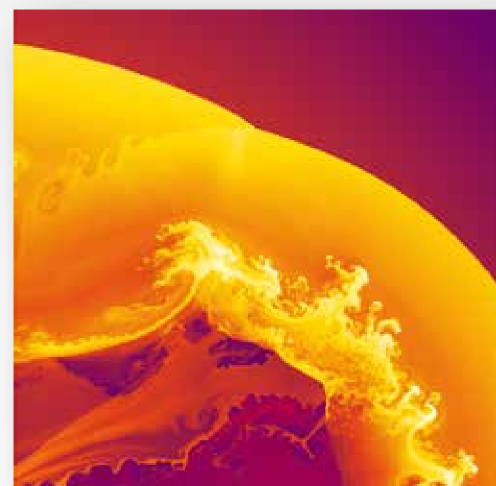


CALE Designs vs SN Model

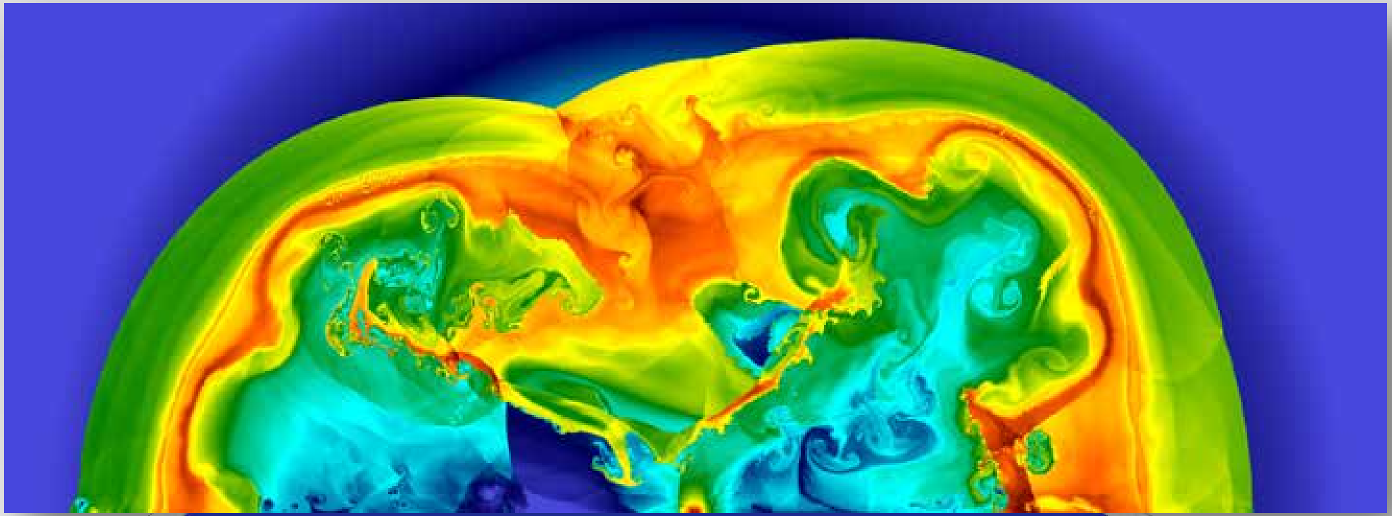


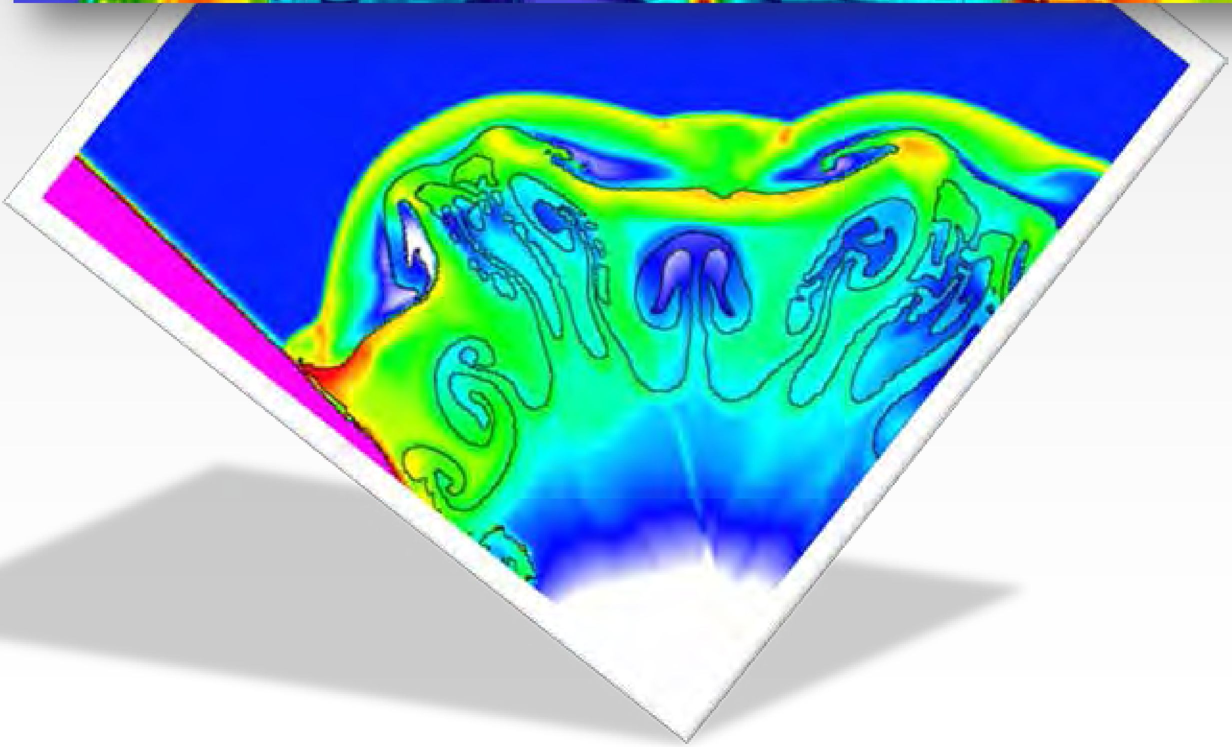






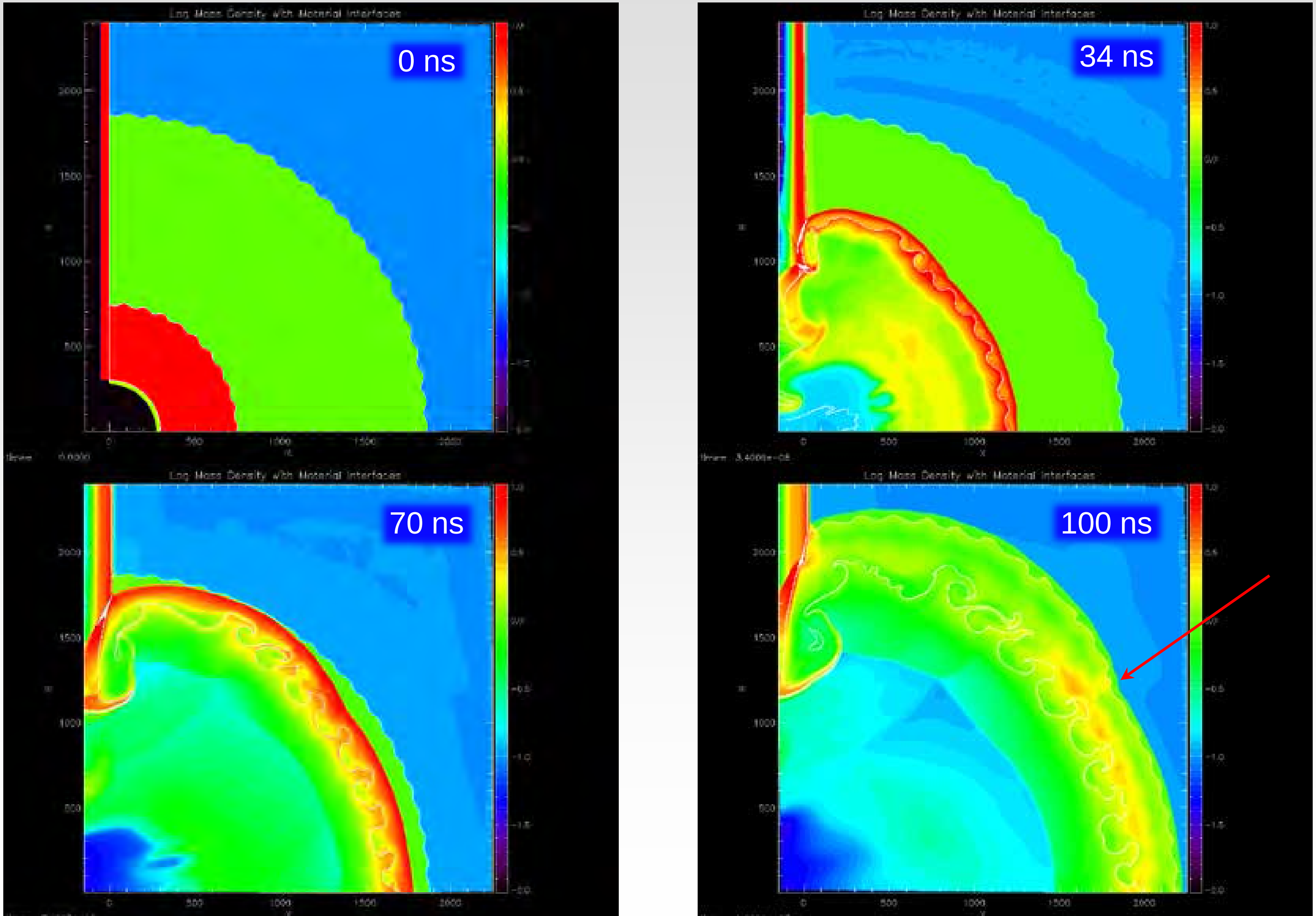
CALE Designs vs SN Model





News: CRASH DivSNRT

by Mike Grosskopf



Proposed Schedule of Shots

FY13

Shot Number	Target Type	Perturbation between interfaces	Drive	Diagnostic Technique	Note
1	hemispherical 2 layers	none	80-300kJ 3ns	radiography	drive test, RT/RM at a nominally smooth interface
2	as above	$(kA)_1$	as above	as above	RT/RM at high-Z/med-Z interfaces
3	as above	$(kA)_2$	as above	as above	as above
4	as above	$(kA)_{(1,2)}$	as above	as above	reproducibility test
5	hemispherical 3 layers	none	as above	as above	drive test, RT/RM at a nominally smooth interface

FY14

3 layer target studies, demonstrate Imaging X-ray Thomson Scattering technique

FY15

3 layer target studies with aspherical shocks with radiography and IXTS

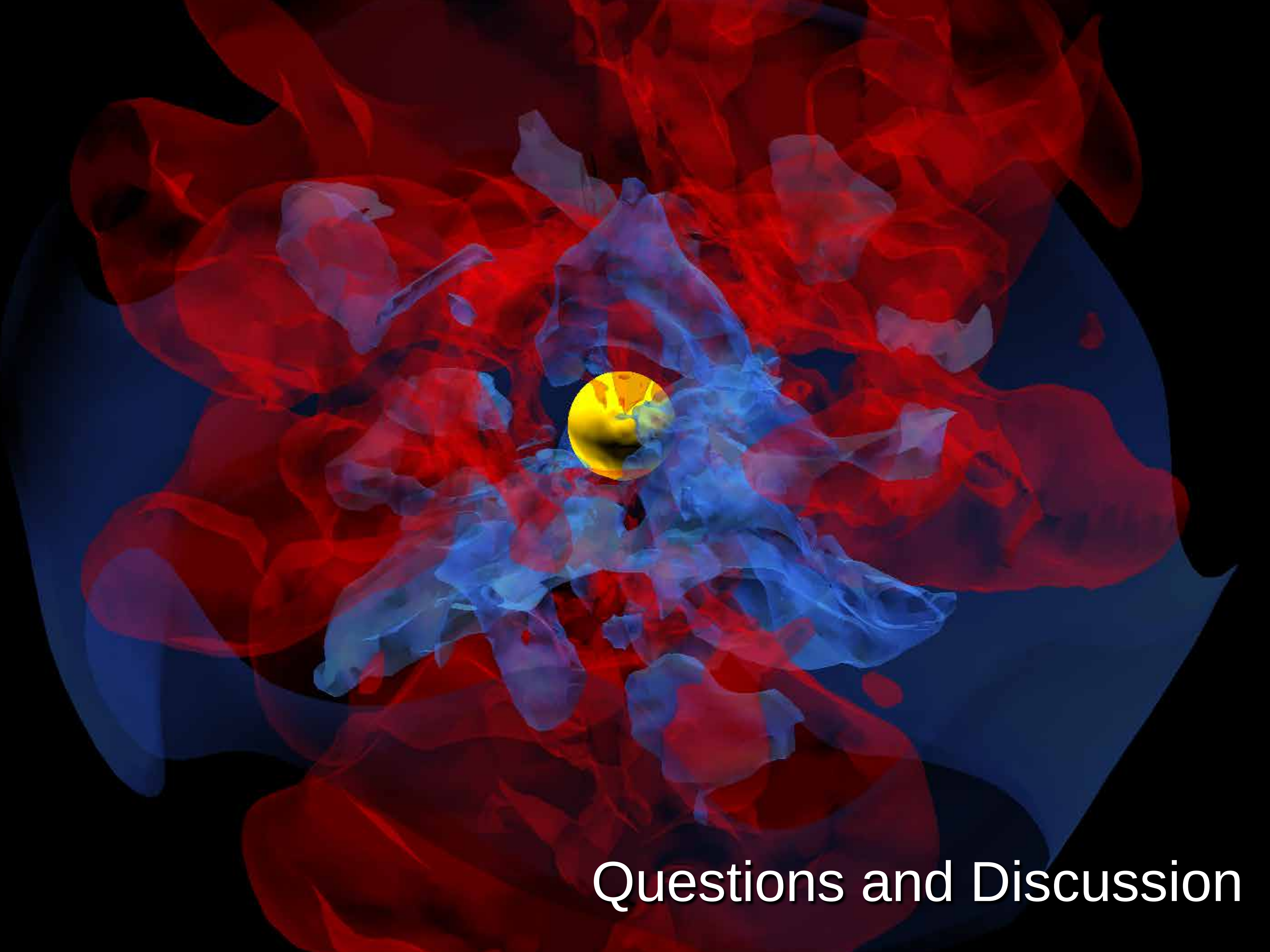
Diverging Supernova Explosion Experiments on NIF

Purpose

- This experiment attempts to observe extensive Rayleigh-Taylor driven mixing in the exploding massive stars.
- Data will give physics insights of inter-shell penetration outwards to surface via turbulent mixing, shell breakouts, growth of secondary instabilities, vorticity-enhanced mixing.

Comments

- NIF is the unique facility enabling studies with spherical targets (diverging flow geometry)
- Natural continuation of the previous work on Omega
- New diagnostics (IXTS, Dante, proton radiography…) in addition to standard diagnostics (x-ray radiography)
- 15 shots starting in FY 2013



Questions and Discussion